Two copies of this report were delivered to Dr. G. Fishman (MSFC) on March 30, 1990.

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W. Paciesas continued to support BATSE in meetings and reviews related to testing, calibration, and mission operations and data analysis software development. He is the BATSE representative on the GRO Data Operations Group (GRODOG) and the GRO Users' Committee. In this regard he provided BATSE inputs in development of the GRODOG Report which was finally issued in July, the NASA Research Announcement for the GRO Guest Investigator Program which was finally issued in January, and the GRO Project Data Management Plan which was released in draft form in February. Portions of this material were used as the basis for an invited paper presented by Paciesas at the GRO Workshop in April which was also included in the Workshop proceedings (Paciesas et al., Appendix A).

Paciesas served as BATSE Mission Operations Software Development Manager and also chaired the Level V Configuration Control Board for the MOPS software. The MOPS Software Test Readiness Review was held on September 13 and portions of the software were used to support GRO End-to-End test #2 on October 2 & 4 and End-to-End test #2A on November 30. During the period of performance of this delivery order the following units completed unit testing and were placed under configuration control: SENDER, SEND_MESSAGE, INST_MODEL_EDITOR, SOURCE_CATALOG_EDITOR, CHECK_CPU_MEMORY, X25_MANAGER, GET_DATA, GET_TIME, SET_QUALITY_FLAGS, ADD_QUALITY_FLAGS, and SPECIFY_QUALITY_MASK. Phase 1 of software formal testing began in November but the beginning of phase 2 of formal testing is not expected to begin until May 1990. P. Moore provided administrative assistance in the MOPS software development effort and was also given the responsibility to code and test the BURST_DISPLAY unit. Paciesas and Moore compiled and edited the first draft of the MOPS Software User's Manual which was distributed on September 6.

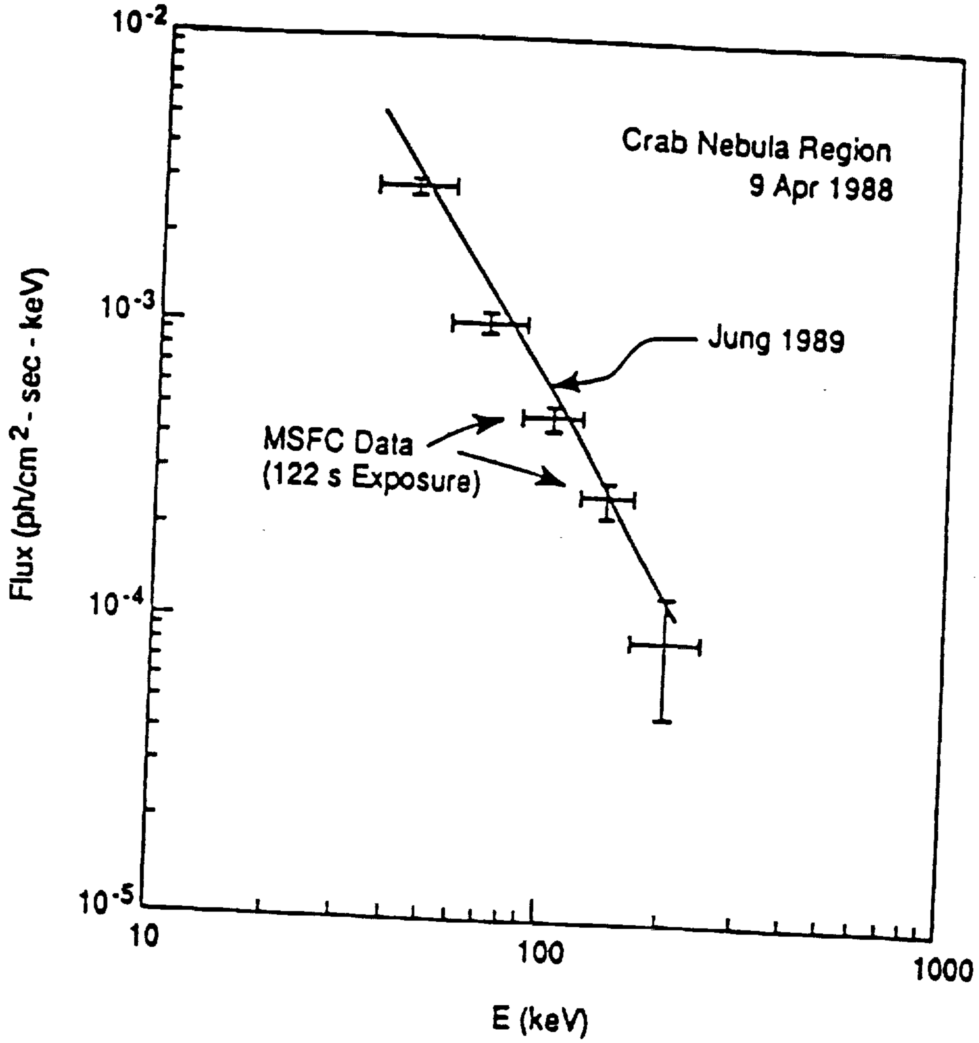
Paciesas also served as scientific liaison overseeing development of the BATSE Spectral Analysis Software (BSAS) by GSFC. G. Pendleton assisted in scientific validation of the model-independent spectral deconvolution algorithm developed for BSAS by B. Schaefer (GSFC). Pendleton and K. Hong analyzed data from balloon flights of BATSE-type detectors and showed that the known spectrum of the Crab Nebula could be satisfactorily reproduced using Schaefer's technique (Figure 1). The progress of BSAS software development was reviewed at the BATSE Science Team Meeting on Nov. 8 and at the GRO Project Software Review on Jan. 23. The first build of the software completed testing in February and was received by MSFC for installation in early March. The build included the modules REDUCE, MODFIT, QFIT, QPHOTN, PHOTON, and MATRIX, plus INGRES tables and some additional utilities for generating test data.

G. Pendleton has led the joint UAH/MSFC effort to develop matrices suitable for use with the BSAS spectral deconvolution algorithms. He presented some of the results at the GRO Workshop on April 10-12 in a poster paper entitled "The BATSE Detector Response Matrices" (Pendleton et al., Appendix B). He also summarized plans and progress at the BATSE Science Team Meeting

(Nov. 8) and the GRO Project Software Review on Jan. 23. Paciesas presented some of the calibration results at the SPIE Workshop on EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy and Atomic Physics during August 7-11 (Paciesas et al., Appendix C).

Paciesas supported the BATSE thermal/vacuum test at TRW in early August. Pendleton supported instrument data runs at TRW in October.

The following subcontractors supported this delivery order: Dr. Jon Hakkila (Mankato State U.) visited UAH and MSFC on March 31 to discuss algorithms for analysis BATSE data to derive burst sky distributions, and Mr. Christopher Starr (Cal Tech) visited UAH and MSFC on June 12 to discuss pulsar timing algorithms for BATSE data analysis.



Hard X-ray spectrum of the Crab Nebula obtained with a 112 s observation on the balloon flight of April 9.1988. The data have been deconvolved using a model-independent inversion algorithm. Shown for comparison is the spectrum obtained by Jung (1989).

Figure 1

Appendix A

(Published in the Proceedings of the GRO Science Workshop)

The BATSE Data Analysis System and Implementation of the Guest Investigator Program

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ABSTRACT

The Burst and Transient Source Experiment (BATSE) detects sources by looking for time variability, either intrinsic to a source (such as γ-ray bursts or pulsars) or induced by earth occultation. Techniques for analysis of the data are dependent on the nature of the variability; moreover, the BATSE data are formatted differently for the different analysis techniques. Certain software functions (such as spectral deconvolution) are useful for all sources once the data have been processed sufficiently. We describe herein a set of software packages which will be used to analyze the BATSE data. We also summarize the nature of the data bases which are produced during the analysis and discuss their potential availability for guest investigations.

The primary facility for analysis of BATSE data will be located at NASA/Marshall Space Flight Center (MSFC). Additional facilities at NASA/Goddard Space Flight Center (GSFC) and the University of California, San Diego (UCSD), will be capable of implementing a subset of the functions of the primary facility. Guest Investigator support will be available at the primary analysis facility during the GRO mission.

1. Description of Data Analysis Flow

BATSE data is transmitted daily from the Packet Processing Facility (PACOR) at GSFC to MSFC via the GRO Data Distribution and Command System (DDCS) in increments of one day. Figure 1 illustrates the flow of data after receipt at MSFC. Storage of the raw data in the BATSE data archive is a mission operations (MOPS) function. The MOPS functions which relate to data analysis also include first-cut monitoring of data quality, monitoring of detector gain and resolution, calculation of various secondary spacecraft parameters such as the local magnetic field, and quick-look science analysis such as first-cut burst location. The MOPS functions also include distribution of a portion of the raw data to co-investigators at GSFC and UCSD.

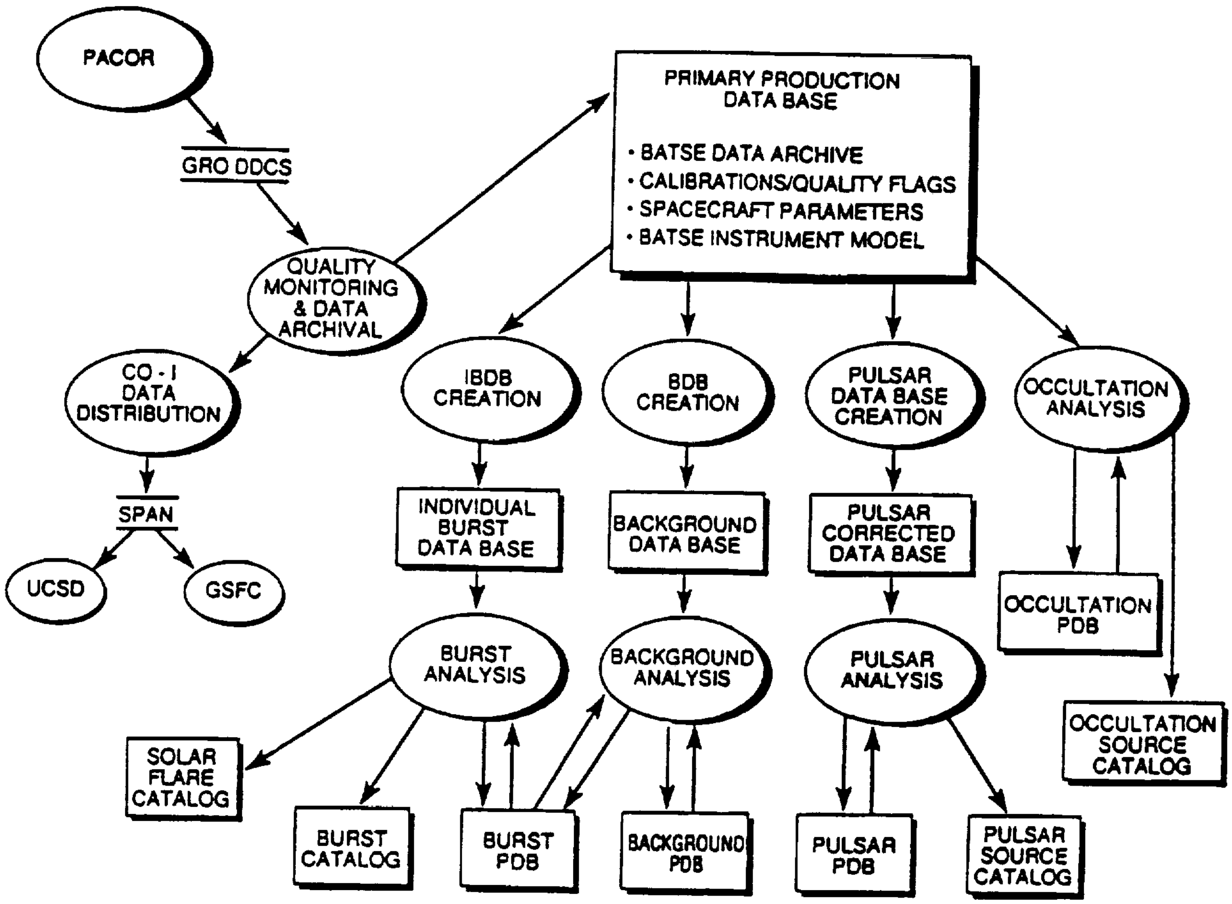

Figure 1: BATSE Data Analysis Flow Diagram

The BATSE data archive is stored on the Marshall Archival System (MARS), an optical disk storage system which is maintained by MSFC for archival of flight data from various experiments. The other components of the primary data base are stored initially on magnetic disk, with archival backups to either local optical disk or magnetic tape. Analysis using a particular technique generally will proceed by generation of the appropriate secondary data base from the primary data base using the raw data combined with the calibration data, quality criteria, spacecraft parameters, and the BATSE instrument model. (The occultation analysis is expected to be an exceptional case, as discussed below.) Subsequent analysis results and processed data are stored in tertiary Processed Data Bases (PDB's) which are managed using the commercially-available INGRES data base management system.

Burst analysis is the primary BATSE science objective. The Individual Burst Data Base (IBDB) which is produced for burst (and solar flare) analysis contains essentially the raw data dump of the on-board burst memory together with associated background data. Burst analysis software performs gain correction, constructs spectra and time histories with optional rebinning and background subtraction, and stores the accumulated data in the Burst PDB. Burst analysis functions include burst location, temporal analyses (Fourier power spectra, epoch folding, etc.), time-resolved spectral deconvolution, display of temporal evolution of spectral-fit parameters, and derivation of parameters for global studies such as $\log N/\log S$. Intermediate and final results may be stored in the Burst PDB. Burst and solar flare catalogs are maintained and will be made available for public access.

Pulsar analysis is a secondary BATSE science objective. Production of the Pulsar Corrected Data Base (PCDB) takes one of two forms depending on whether on-board folding has been performed or not. If folded on-board, various corrections for folding-period offset, overflows and unequal bin widths must be applied in addition to the standard Doppler corrections. If on-ground folding is to be performed, the PCDB consists mostly of raw rates, possibly binned in time and/or energy, with appropriate Doppler corrections. Pulsar analysis includes functions for light curve display, light curve model fitting, time-resolved spectroscopy, and display of temporal evolution of fit parameters. Intermediate and final analysis results may be stored in the Pulsar PDB. A pulsar source catalog is maintained and will be made available for public access.

The Background Data Base (BDB) is intended to facilitate studies of background variations which may lead to development of improved background models and/or discovery of non-triggered bursts or intermediate-timescale transient events. Software analysis tools consist primarily of display programs, spectral analysis functions such as line-fitting, and temporal search algorithms. Intermediate and final results may be stored in the Background PBD. Application software may be developed by users as required for particular investigations.

The monitoring of persistent and long-term transient sources using earth occultation is also a secondary BATSE objective. This analysis is expected to be particularly complex, requiring careful scientific monitoring. The software is expected to evolve considerably as the mission proceeds; hence, data base definition is still in progress. Present planning indicates that creation of a secondary data base as in the other types of analysis is probably not useful. The major occultation analysis software would work directly on the raw data, developing source time histories with modest spectral resolution which would be stored in the Occultation PDB. Spectral deconvolution of the data may be performed and the results also stored in the PDB.

A primary component of all data analysis is spectral analysis, including line searches and spectral deconvolution. A software package, the BATSE Spectral Analysis Software (BSAS) is being developed for this purpose by BATSE co-investigators at GSFC and it will be transported to other BATSE team facilities at MSFC and UCSD. Though primarily intended for analysis of burst spectra, the package will also be used for any spectral studies in the other analysis modes.

2. Instrument Analysis Center Data Bases

Three types of secondary data bases are produced for data analysis: the Individual Burst Data Base (IBDB), the Background Data Base (BDB), and the Pulsar Corrected Data Base (PCDB). At MSFC, these are created as needed for a specific application from the Primary Production Data Base and generally not archived. The IBDB and BDB formats are used to distribute a subset of the BATSE data to co-investigators at GSFC and UCSD, where local archives of these data bases are maintained. These data bases generally consist of essentially raw data which satisfies certain quality criteria, together with associated calibration parameters, spacecraft parameters, and pointers to relevant instrument model data (primarily response matrices). Pulsar data undergo some corrections to eliminate certain types of overflow conditions. The data may be summed over selected time and/or energy domains. Occultation analysis does not lend itself to useful compression at this level, and we do not anticipate creating a secondary data base for this purpose.

The tertiary PDB's contain gain-corrected spectral files and time-history files, together with various other files of intermediate or final analysis results. There are four PDB's: one each for burst, background, pulsar, and occultation analyses (solar flares are maintained in the burst PDB).

The spectral and time-history files are typically binned in the energy and/or time domains relative to the secondary data base. Header relations and pointers to each of these files are maintained and managed with INGRES. INGRES also effectively maintains a history of analyses performed for each source. Individual users will typically have their own copy of a subset of the PDB while a particular investigation is in progress. Selected results and intermediate data files may then incorporated into the institutional master copy of a PDB at the user's option (appropriate privileges are required). Inspection of the institutional PDB thus enables a quick survey of work already completed on a particular source and helps to eliminate duplication of effort.

3. Public Data Bases & Data Products

Within the GRO Guest Investigator (GI) program (Bunner 1989) a significant distinction is made between high-level and low-level data. The high-level data products will be analyzable in a relatively independent manner whereas use of low-level data will require close collaboration with the Principal Investigator (PI) team, typically involving a period of residence at a PI institution.

Any data which can be stored in a BATSE PDB are, in principle, available as high-level data. Standard sets of time-histories and pulse-height spectra (with associated response matrices and calibration parameters) will be produced for each burst, solar flare, pulsar (on-board folding only), and bright occultation source. Requests for non-standard data sets (*e.g.*, different energy or time binning, different burst data types, weaker occultation sources, raw data for on-ground pulsar folding or other temporal analysis) will be considered special processing, and will be honored on a resource-limited basis. High-level data will be available either in Flexible Image Transport System (FITS) format or in the BATSE PDB format. The latter will be useful if the BSAS package is transported to a GI system.

The remaining BATSE data (secondary data bases or, in the case of occultation analysis, the primary data base) are available to GI's as low-level data. Typically, use of these data products would involve spending some time at MSFC, since no resources have been allocated for GI visits to GSFC or UCSD. Once the GI attains sufficient familiarity with the instrument characteristics and analysis techniques, arrangements to transport relevant software and/or low-level data to another institution will be considered on a case-by-case basis.

Catalogs of BATSE observations/investigations of bursts, solar flares, occultation sources, and pulsar sources will be generated during data analysis. Data analysis catalogs of bursts, solar flares, occultation sources, and pulsar sources will be available for public inspection via remote logon over the Space Physics Analysis Network (SPAN). Access via other means is being considered.

The BATSE burst and solar flare trigger signals are sent in real time to the other instruments on the GRO. As part of MOPS, BATSE will provide additional information such as first-cut location of bursts to interested GRO instrumenters via the GRO DDCS. A similar service will be available via SPAN using VAX mail. Some form of public access via SPAN will be available; the details have not yet been defined.

4. Data Analysis Environment

The BATSE data analysis environment at MSFC consists entirely of Digital Equipment Corporation (DEC) VAX systems in an ethernet cluster physically located in the Space Science Laboratory (SSL; building 4481). Machines on the cluster which are available for BATSE data analysis include a VAX 11/780 and a VAX 8250. Aproximately 600 Mbyte of magnetic disk storage is available for exclusive BATSE use. Hardware which is planned for purchase in FY89 includes three VAXstation 3100's with a total of ~500 megabytes of additional disk storage. Four additional VAXstation 3100's plus an additional 600 Mbyte disk drive for the SSL cluster are planned for purchase in FY90. All systems operate under VAX/VMS. Peripherals available on the cluster include line printers, laser printers, 6250 bpi magnetic tape drives, pen plotters, and an optical disk Write-Once/Read-Many (WORM) drive.

The MARS is used for archival of the raw BATSE data. It is a custom-built optical disk WORM storage system which is shared with other MSFC projects. The system consists of 128 disks in a jukebox arrangement. Each disk has a capacity of ~10 Gbyte, resulting in a total system capacity of ~1 Tbyte. One year of BATSE packet data takes ~1 % of MARS capacity. The front-end interface to MARS is a VAX system, running VAX/VMS. ORACLE is used to maintain on VAX disk a catalog of the data archive. MARS is located in building 4487 at MSFC; access to MARS is via an Institutional Area Network.

5. Data Analysis Software

We have somewhat arbitrarily specified the BATSE data analysis software in terms of a number of packages. The current development status of the packages varies. Some are almost completely coded, while others are in requirements specification or preliminary design. We discuss each package in the subsections which follow. First, however, some general comments which relate to software portability are warranted.

- *All BATSE data analysis software runs under VMS.* Use of VMS system-specific calls has been minimized but not prohibited in software development. For software not yet developed, we are considering eliminating such usage. Several packages use proprietary commercial or public domain products which are available in versions which run under other operating systems. We have no plans to perform any tests which would assure that any of our packages which use such software will in fact run under another operating system.

- *Most of the software is written in FORTRAN.* VAX FORTRAN is a superset of ANSI FORTRAN-77. Although all packages are compiled under VAX FORTRAN, some development restrictions exist with regard to use of non-ANSI constructs. Additional restrictions are being considered which may be applicable to future software development.

- For many packages the user shell is a package called Transportable Applications Executive (TAE) which is available from COSMIC (NASA's Computer Software Management and Information Center). Versions of TAE are available for several different operating systems (including UNIX). The PDB's are managed using INGRES, a commercial product which is also available in versions for other operating systems. At least two graphics packages are used: GKS-compatible NCAR Graphics and MONGO.

- The commercial package IDL (or its more recent successor PV~WAVE) may be used in implementing some functions in packages which have not yet entered the coding phase.

5.1. BATSE Spectral Analysis Software (BSAS)

This package is used in all data analysis functions for spectral deconvolution and model-fitting. Routines are available for accumulation and rebinning of spectra from the secondary data bases, background subtraction using several different algorithms, traditional model-dependent least-squares spectral deconvolution, spectral line searches and fitting, model-independent deconvolution using direct matrix inversion, model-fitting to model-independent photon spectral data, display of pulse-height or photon data and model fits, and determination of burst-specific parameters such as fluence. Analysis results are stored automatically in a user version of the PDB and may be stored at the user's option in the appropriate institutional master PDB. The spectral deconvolution is a fairly complex task; however, many astronomers, particularly those with high-energy experience, are familiar with the problems involved.

The package uses TAE, INGRES, and MONGO. In particular, it makes extensive use of INGRES forms for input menus. Graphics hardware which supports Tektronics 4010/4014 standard is required for displays. A certain degree of portability exists because the package is written to be used at three different BATSE institutions: MSFC, GSFC, and UCSD. However, all three have VAX systems running under VMS, and all will have the necessary associated software and graphics hardware.

5.2. Mission Operations

This package is used in performing the daily tasks involved in Mission Operations (MOPS). It includes various routines for communication with the GRO DDCS, monitoring of instrument configuration and performance, mission planning and command generation, instrument model data base management, data archival, and quick-look science. It is also used to distribute data to BATSE co-investigators and GSFC and UCSD via SPAN. It generally operates only on the raw data set from the most recent day. However, files of recent history of selected parameters are maintained; the latter are used as input to certain data analysis functions which maintain a local (non-MARS) archive of certain parameters. Other MOPS functions which relate directly to data analysis include reformatting of data for MARS archival, first-cut data quality monitoring, first-cut burst location, burst time-history display, bright-source occultation monitoring, calculation of secondary spacecraft parameters such as McIlwain (L, B) coordinates, and monitoring of detector gain and resolution. Complexity is moderate in most cases, except for burst location and occultation monitoring, which involve considerable algorithmic subtleties.

The MOPS package uses TAE and GKS-compatible NCAR Graphics. Graphics hardware compatible with 4010/4014 is required for displays. Non-ANSI features of VAX FORTRAN are used extensively. Specific hardware interfaces are required for communication with the GRO DDCS. Although the package was not intended to be used outside MSFC, portions will be adapted for use in data analysis, at which time portability-related improvements may be considered.

5.3. Burst Data Analysis

Some burst data analysis will be accomplished using MOPS software (with minor modifications). BSAS will be used for burst spectral analysis. Additional burst analysis software is required to implement other functions: IBDB generation, optimized burst location, display of sky distributions, sky exposure map computations, isotropy analysis, improved time-history display utilities, burst periodicity studies using epoch-folding or Fourier power spectra, instantaneous burst detection efficiency, etc. This software is still in early development, so portability constraints could be applied if deemed appropriate. Many functions will be implemented using IDL. Some functions are relatively straightforward. Others such as sky exposure map computations are not trivial and require some considerable scientific oversight. Some functions will be require access to the burst PDB and therefore will have an INGRES interface.

5.4. Pulsar analysis

Pulsar analysis software is required to implement various functions: PCDB generation, epoch-folding, Fourier power spectral analysis, lightcurve display utilities, light-curve fitting, pulsar parameter time-history display, etc. This software is in early development, so that portability constraints could be applied where deemed appropriate. Algorithms for these functions are relatively standard. Many functions will be implemented using IDL. Most functions will require access to the pulsar PDB and therefore will have an INGRES interface. BSAS will be used for spectral analysis.

5.5. Occultation analysis

MOPS software will be adapted to use in data analysis for bright-source occultation studies not already performed in MOPS. BSAS will be used for spectral analysis. Some utiltiies are required: sky distributions, source time-history display, etc. Software for this purpose is in early development, so that portability constraints could be applied as appropriate. Complexity is minimal. Additional software is required in order to implement an optimized source search strategy. The algorithms will require considerable refinement in order to reduce systematic errors. IDL will be used extensively in analyses of the systematics. Portability is not expected to be a consideration, since independent analysis of these data is not likely. Some functions will require access to the occultation PDB and therefore will have an INGRES interface.

5.6. Background analysis

Background analysis software is required to generate the BDB and to implement the non-triggered burst search and line-transient search. BSAS will be used for background spectral analysis. Additional software is in early development. Access to the background PDB and burst PDB via INGRES will be required. Systematic subtleties make the background analysis a complex task which is not expected to be performed independently by GI's.

5.7. High-level data base generation

This is a straightforward set of utilities for generation of high-level data for distribution to GI's. The software will extract the necessary data from the appropriate PDB and convert it to FITS format. The package will be developed during the first year of GRO operation.

5.8. Response matrix generation

Sensitivity attainable with both low-level and high-level data products will improve significantly as the instrument model (detector response matrices and atmospheric and spacecraft scattering corrections) becomes more sophisticated. The improvements will result from better Monte Carlo simulations as well as empirical adjustment using data from sources with known locations and/or spectra (*e.g.*, Crab Nebula, solar flares, orbiting nuclear reactors). Software for Monte Carlo modeling exists at MSFC but neither portability nor user-friendliness were seriously considered during development. By nature, the Monte Carlo studies require intensive scientific involvement. Empirical adjustment studies will be performed using the existing analysis routines, with possible use of IDL. Refinement of the response matrices is a major function of the PI team. Our approach to response matrix generation is described by Pendleton *et al.* (1989).

6. Support for Guest Investigators

The GRO science office is expected to provide one scientist to act as GI liaison on a half-time basis. The BATSE team plans to designate one scientist (half-time), one programmer (full-time) and one data technician (half-time) to provide additional GI support. At least one VAXstation 3100 will be available to GI's on a priority basis. The link to SPAN will enable remote logon and access to catalogs, data bases, and software (with appropriate restrictions). Although portions of the BATSE data and software are available at GSFC and UCSD, there are no plans to provide additional resources at either of these sites to support GI's.

7. Data Access Schedule and Mechanisms

Access to low-level data will be available at MSFC beginning in the first year. We anticipate supporting ~2–4 GI's during the first year. Standard high-level data products will be available from MSFC in a *Rev. 0* release during the second year. We anticipate several revised releases of standard high-level data at intervals of about a year. The standard high-level data products will also be incorporated into NASA's Astrophysics Data System (ADS). We plan to deliver data in FITS format to the appropriate ADS node within one year after receipt of data in usable form.

The BATSE burst catalog, solar flare catalog, occultation source catalog, and pulsar source catalog will be available for public access through MSFC during the second year. It is expected that BATSE catalogs will eventually be incorporated into the ADS Astrophysics Master Directory; the schedule for this has not been defined.

ACKNOWLEDGEMENTS

Development of BATSE mission operations and data analysis software is a major task involving too many people to name individually. We appreciate the efforts of staff members of the Space Science Laboratory of the NASA/Marshall Space Flight Center and the Laboratory for High Energy Astrophysics of the NASA/Goddard Space Flight Center as well as those of contractor personnel. The major contractors include Boeing Computer Support Services, Inc., New Technology, Inc., the University of Alabama in Huntsville, Science Applications Research, Inc., and the University of Maryland.

We are also grateful for expert advice and assistance from Jesse Maury, the GRO Project Software Manager.

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Appendix B

(Published in the Proceedings of the GRO Science Workshop)

The BATSE Detector Response Matrices

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Abstract

The detector response matrices for the BATSE large area detectors and spectroscopy detectors are being generated using EGS Monte Carlo simulations that are verified by comparison with experimental data. The format of this procedure is discussed. Data exhibiting the angular response of the detectors are presented. The format in which the detector response matrices are to be stored for general access is described. Future work for refining the matrices is outlined.

1 Introduction

The detector response matrices for the BATSE detectors are necessary for any spectral analysis and for burst location. These matrices charactrize the detector output for a given energy input. The spectral response functions for the BATSE detectors, particularly the large area detectors, exhibit significant Compton tails at higher photon energies. Therefore precise characterization of the detector response matrices is required for any type of photon spectrum reconstruction. Also a thorough understanding of the angular response of the large area detectors is necessary for reliable burst location. Scattering of photon flux off the atmosphere is addressed elsewhere and is not discussed in this paper.

2 Experimental Verification of Monte Carlo Simulations

A comprehensive set of BATSE detector tests have been performed. Those tests focusing on detector spectral response functions are the Angular Response tests and the Absolute Efficiency tests. In these tests the detectors were exposed to monoenergetic nuclear γ-ray sources and spectra were collected. Although a variety of sources were employed, the detector response functions were measured only at the energies of the γ-rays that the nuclear sources produced.

In order to extend the detector response functions between the energies measured in the tests Monte Carlo simulations are employed. The accuracy of the simulation results is confirmed by comparison with the experimental test results. Also, detailed analysis of the simulation results yields an improved understanding of systematic characteristics of the detectors and of the test environment. The simulations can be used to extend the detector response matrices to energies above 3 MeV where measurements have not been performed.

In order to accurately reproduce the experimental measurements with Monte Carlo calculations the detector geometry and test environment geometry must be simulated in detail. These simulations are performed with the EGS electron-photon shower code (Ford *et al.*) and a general geometry routine written by the principal author. Figure 1 shows an outline of the geometry used for the large area detector simulation. The figure is a nearly edge on view of the detector geometry surrounded by objects present in the test environment. Shown are the anticoincidence assembly, the detector crystal assembly, the light collection cone, and a compressed volume for the detector base.

In figure 2 the detector is shown in the angular response test geometry. Here the detector rests on a raised stand and is exposed to a collimated monoenergetic photon beam. The sources used in the angular response tests were placed in a lead collimator with an opening angle of 11.5°. In these tests the detector module was rotated about a vertical axis to positions spanning 360°. Each position corresponded to a specific angle between the detector normal and the incident photon beam. The detector response for both the large area detectors (LAD's) and the spectroscopy (SD's) detectors was measured at each position. The data obtained characterize the angular response of both the LAD's and SD's.

Figure 3 shows the spectra obtained at various angles for the LAD's and SD's from exposure to a Cs^{137} source (a 662 keV γ-ray source) during the angular response tests. The numbers on the graphs themselves (0 degs , etc.) identify the response functions at specific angles between the detector normal and incident photon beam direction. The angular response of the LAD's is quite strong, as intended, where as the angular response of the spec detectors is not as pronounced.

Figure 4 shows spectra generated using the Monte Carlo simulation for an LAD exposed to a Cs^{137} source at 0° and at 90°. The spectra were obtained by taking the energy deposition spectrum in the LAD crystal and subjecting it to two procedures. First the radial response of the crystal was taken into account; the luminosity response measured by the LAD phototubes to an energy deposition at the edge of the LAD crystal is about 85% of the response measured due to an energy deposition at the center of the crystal. This behavior has been measured experimentally and can be characterized by a radial response function. In order to incorporate this feature of the detector response into the Monte Carlo spectra, each energy deposition was adjusted by the radial response function before being added to the energy deposition spectrum. Secondly a statistical broadening function dependent on energy was applied to the data to produce the spectra shown in figure 4. These procedures will be described in much greater detail in a series of forthcoming papers.

3 Detector Response Matrix Storage Format

The actual detector response matrices will be generated in a comprehensive set of Monte Carlo production runs this summer and fall. The detector response matrix data will be stored in rows where each row corresponds to the detector response at a specific input energy. An example of the shape of such a row is the Cs^{137} spectrum which shows the detector response to 662 keV γ-rays. Each of these rows will consist of a 60 point piecewise linear fit that will extend from the detector threshold to 150% of the photopeak energy. What this means is that the spacing between points in a row will be $E_{in} * 1.5/59$. (E_{in} being the input energy). This format results in a compressed matrix for storage.

This storage format has a number of advantages. Most features of the detector response matrix, are linearly dependent on input energy. Therefore if it is necessary to determine the detector response at an input energy between two of the rows of the response matrix it will be more accurate to extrapolate between two rows in the compressed matrix space. For example in the compressed matrix space the photopeaks of different input energies line up and the extrapolation between the peaks is more accurate. This is the extrapolation technique employed in the creation of rebinned detector response matrices when calculating the values at bin edges between matrix rows. The matrix can then be recast in conventional energy space for use in analysis. The restoration of the matrix to conventional uncompressed form will be an automatic feature of the spectral analysis software (Schaefer *et al.*,1989). The user will select the binning and energy range desired and the software will produce the appropriate matrix in standard uncompressed form. Therefore the compressed matrix storage format will not inconvenience the user.

Another advantage of the compressed format is that it optimizes the ratio of information content to storage space for the matrices. This is true for two reasons. First, the uncompressed matrix has a large number of zero elements at output energies above the input energy. These are not present in the compressed format. Second, since the detail necessary at lower energies is not necessary at higher energies, no information is gained by storing the matrix in uncompressed form.

In the compressed format any number of rows can be stored (i.e. the format is not limited by the constraints of a square matrix). This means that we can store the SD response matrices over the energy range from 15 keV to 100 or more MeV. Storing such a matrix in conventional form with a 2 keV accuracy (necessary at around 15 keV) would require something like a 50,000 $\times$ 50,000 element array which is way too big. The compressed matrix format allows us to store the same data in a 60 $\times$ 100 or 200 element array whose size we can adjust depending on the accuracy desired.

Finally the angular response must be addressed. The matrix format above applies to a detector response matrix calculated for γ-rays at one particular angle of incidence with respect to the detector normal (one particular polar angle). Azimuthal variations in the detector response matrices at fixed polar angles are not considered in the first generation of detector response matrices. However the detector response matrices must span polar incidence angles from 0^o to 90^o or more. To store these matrices efficiently each element of the compressed matrix is parameterized in θ, the polar angle of incidence. At present a 4 coefficient parameterization of each matrix element is calculated. The matrix elements at incidence angle θ are calculated from

$$X = A * F_1(\theta) + B * F_2(\theta) + C * F_3(\theta) + D * F_4(\theta)$$

This parameterization technique was adopted because of the complexity of the angular response of the LAD's. Here each element of the array can vary with θ independently. Therefore it can handle virtually any θ dependent variations in the response matrices. At this time the four functions $F_1(\theta)$ through $F_4(\theta)$ are those of a general cubic polynomial. If during the matrix data generation phase we find another set of four functions that produce a significantly more accurate fit to the angular dependence of the detector response we will use those. The coefficients A, B, C, and D are the quantities that will be stored. This way the entire response matrix set can be stored in four compressed matrices of coefficients. This paramaterization is a structure internal to the spectral analysis software. The software will automatically generate the uncompressed matrix for the appropriate angle of incidence for each detector.

As our understanding of the detector response matrices increases, azimuthal dependence and individual detector characteristics can be incorporated into the response matrix set. This will result in an increase in the number of parameters per matrix element and separation of the eight individual detector response matrix sets. The improvements in detector response will be generated with the GRO mass model code after it is fully tested and compared with experimental tests. The GRO mass model code still under construction will be tested using the data obtained during the GRO source survey test. In this test γ-ray sources were exposed to the entire spacecraft with the BATSE modules attached in flight configuration. Data were collected from the entire BATSE system operating in this case as an all spacecraft monitor. The data will be used to determine the contribution of spacecraft scattering to the response matrices. They will also be used to test the accuracy of the mass model geometry code. The test setup will be simulated in detail and the simulated spectra generated will be compared with the data collected to verify the operation of the code. Once the simulation code is shown to be operating correctly the geometry for the spacecraft in orbit will be input. With this simulation it should be possible to incorporate azimuthal dependence into the detector response matrices.

4 Implementation of the Matrices

The basic response matrices including angular dependence will be implemented in the software before launch. Matrices with azimuthal dependence will be implemented as soon as the simulation code can generate them. The simulation software will be maintained in working order in case more detailed knowledge of some aspect of detector response is desired.

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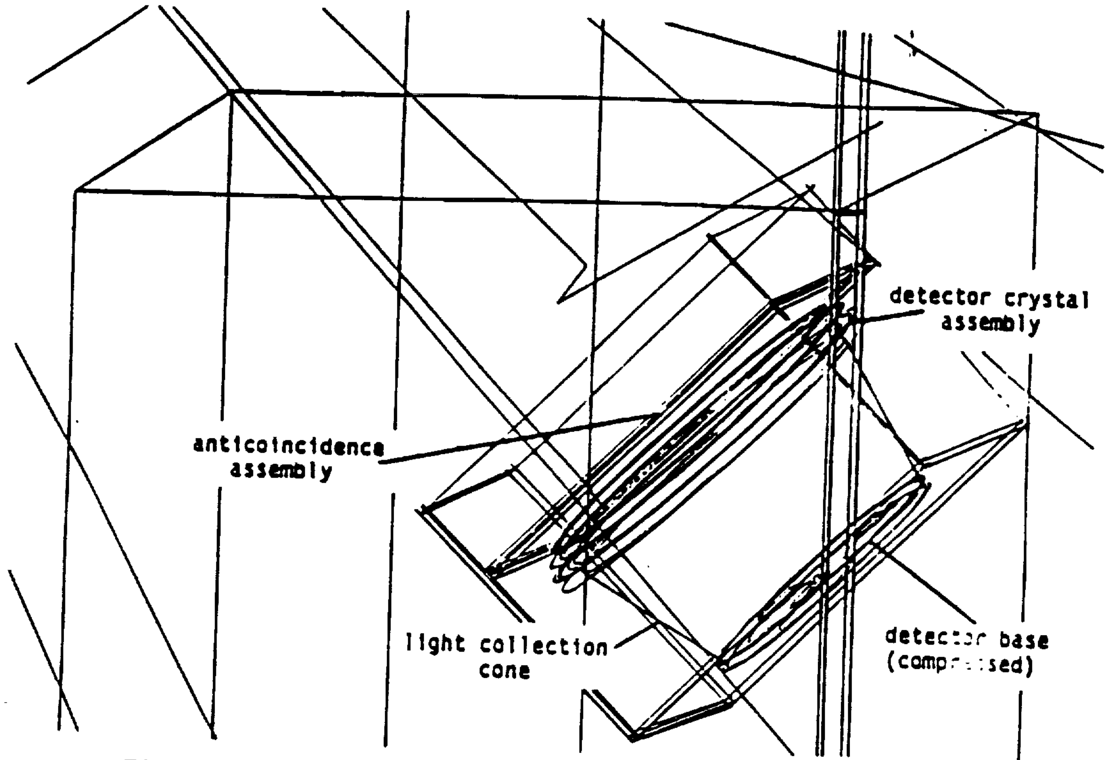


Figure 1. Diagram of simulation geometry used for the Large Area Detector. The detector appears inside a rectangular volume with the outlines of objects in the Absolute Efficiency test environment distributed around it.

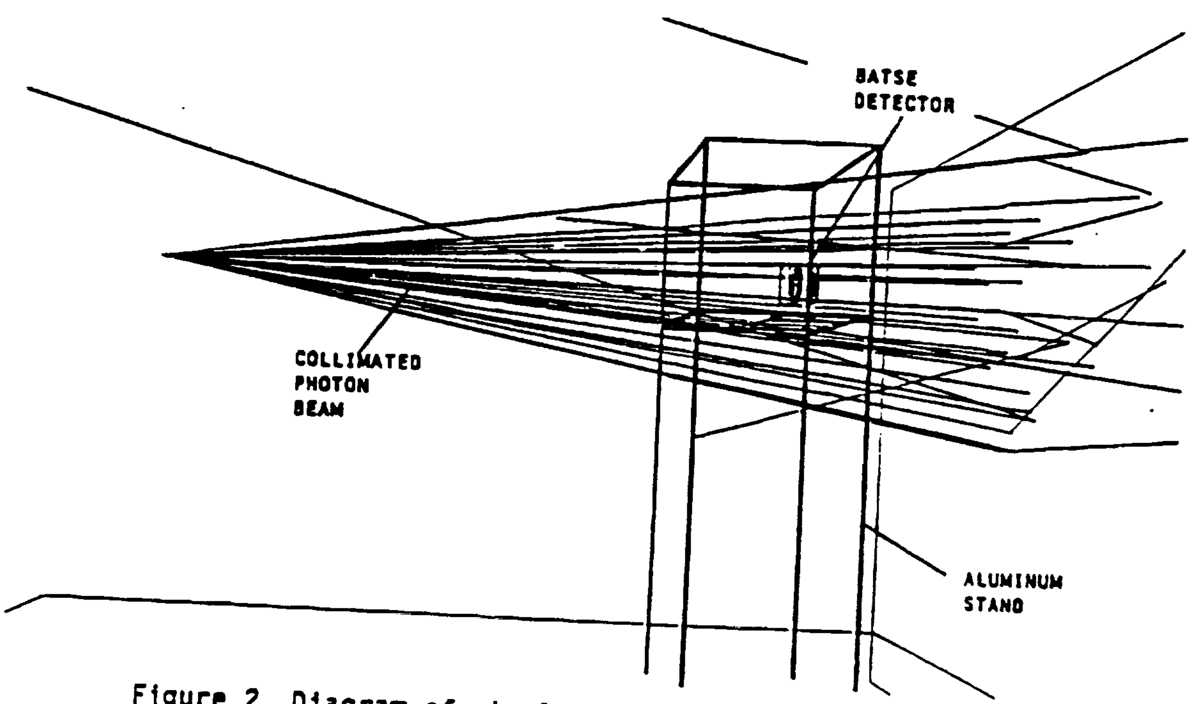
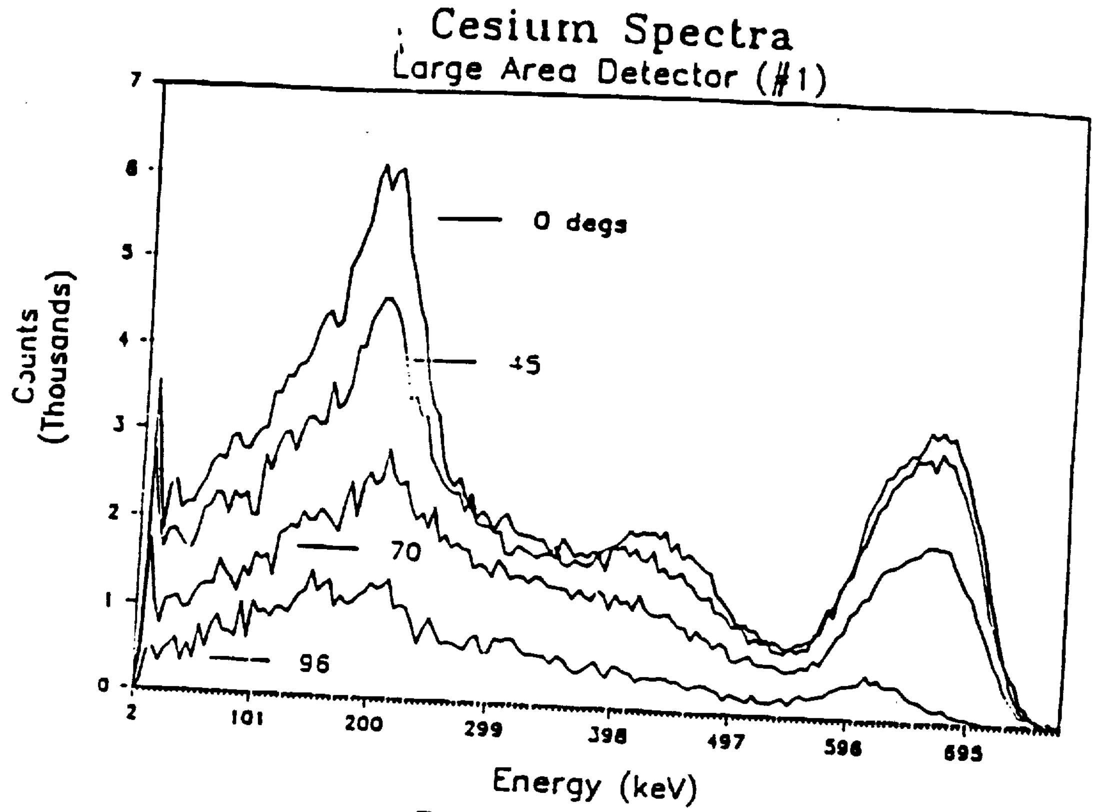


Figure 2. Diagram of simulation geometry used in the Angular Response tests. The detector rests on a raised platform and is exposed to a collimated photon beam.



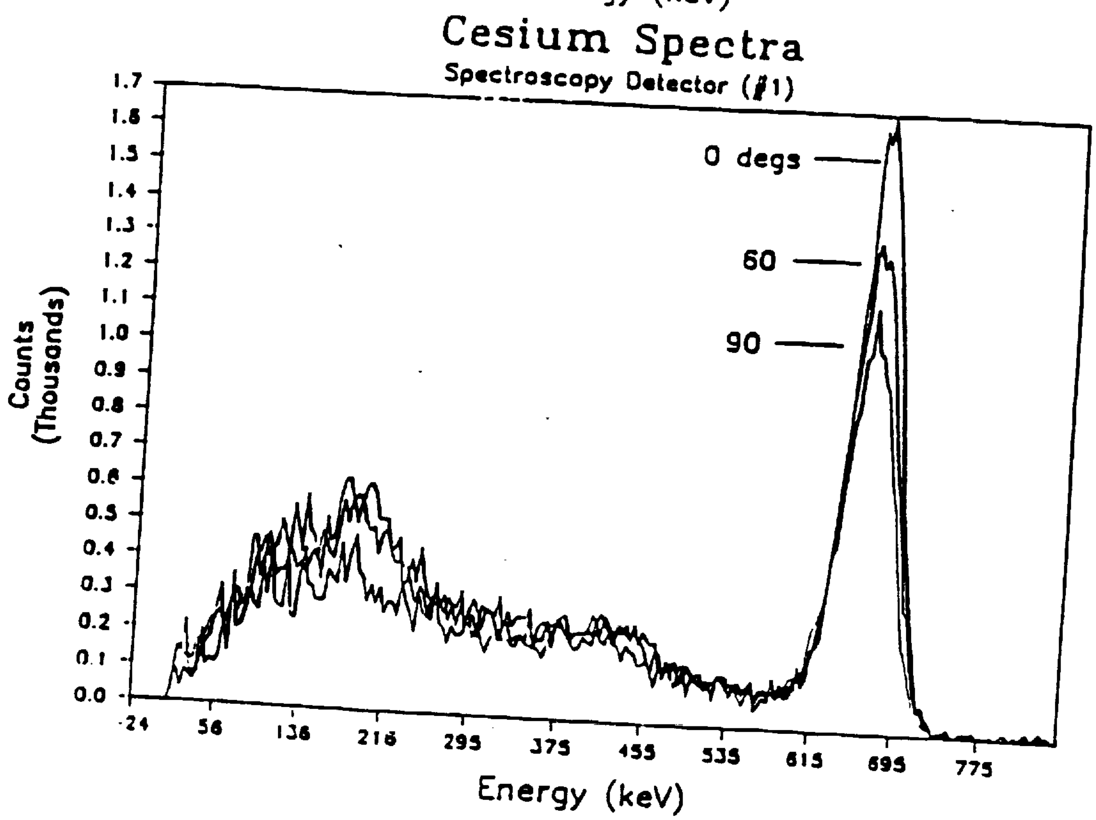


Figure 3. Measured detector response spectra obtained at various angles for the LAD and spec detectors from exposure to a Cs 137 source in the Angular Response tests.

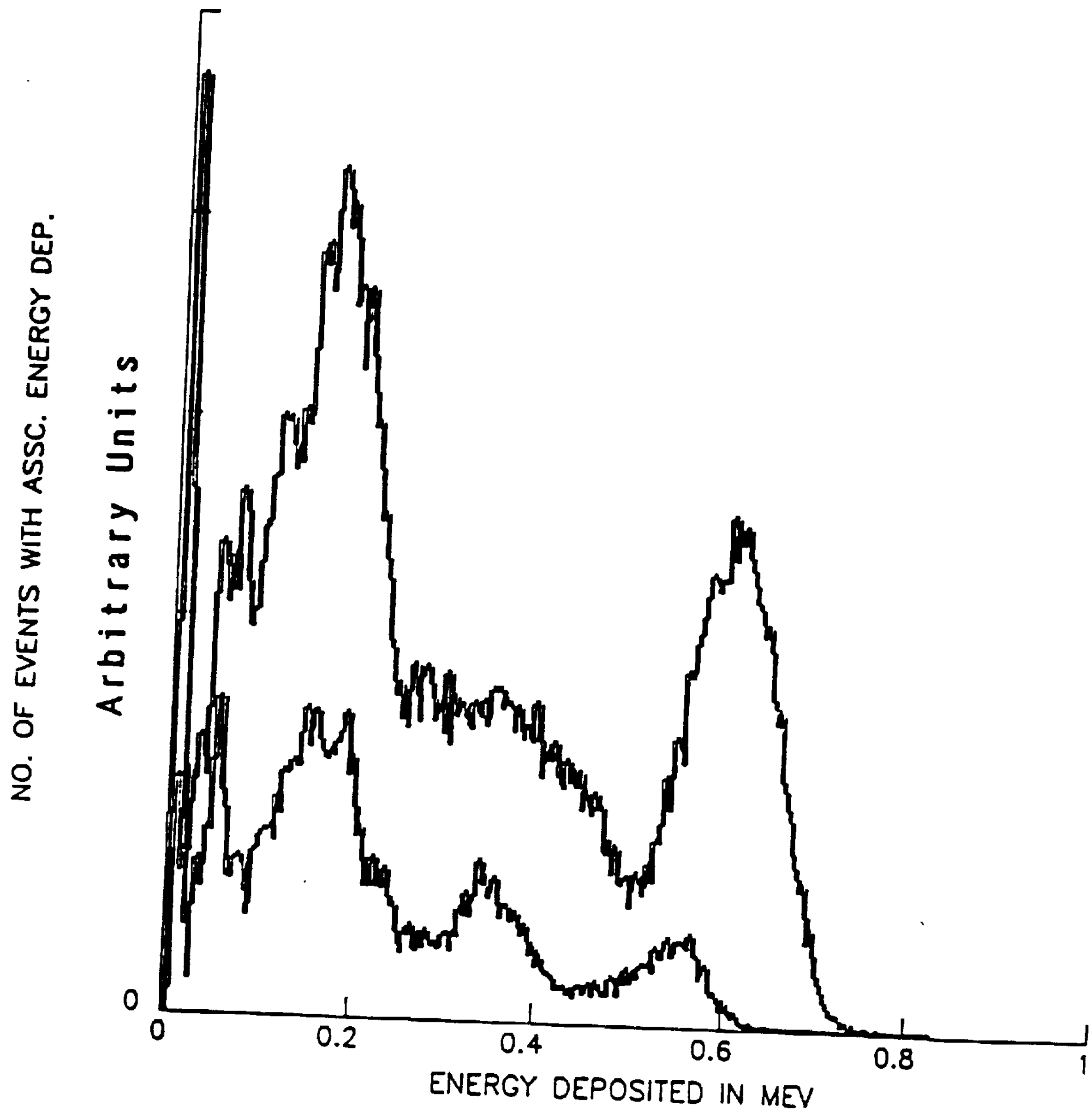


Figure 4. Monte Carlo generated spectra for LAD exposure to Cs 137 source in Angular Response geometry. Spectra at 0 and 90 degree angle of photon incidence are shown. Axes are not normalized to experimental spectra.

Appendix C

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Performance of the large-area detectors for the Burst and Transient Source Experiment (BATSE) on the Gamma Ray Observatory

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ABSTRACT

The Burst and Transient Source Experiment (BATSE), one of four experiments on the Gamma Ray Observatory (GRO), is expected to provide the most sensitive observations of γ-ray bursts yet obtained, as well as to provide long-term monitoring of hard x-ray and low-energy γ-ray emission from bright pulsating sources, transients, and solar flares. Eight uncollimated modules, positioned at the corners of the spacecraft to provide an unobstructed view of the sky, detect sources by various techniques based on time variability. Use of detectors with anisotropic response allows location of γ-ray bursts to be determined to an accuracy of $\sim 1°$ using BATSE data alone. The completed BATSE underwent intensive testing and calibration prior to its delivery in October 1988 for integration on the GRO. We describe the instrument and summarize the results of the testing and calibration as they relate to characterization of systematic uncertainties in BATSE burst location.

1. INTRODUCTION

A principal difficulty in understanding the nature of γ-ray bursts is that the distance to them is not known. Identification of the bursts with known objects could provide this information, but attempts to do so have generally been unsuccessful. The situation is further complicated by the fact that distinct classes of bursts may have different properties and physically different origins. BATSE will detect and localize hundreds of γ-ray bursts per year. Such a large sample will be required in order to infer the spatial distribution of the various classes, providing in turn the possibility of associating the bursts with other astrophysical objects. BATSE also has unprecedented sensitivity for performing spectroscopy and studies of rapid variability in bursts.

We describe herein some of the testing, calibration, and simulation that are required in order to assure that BATSE meets its design goals. Specifically, we consider the problem of burst location and its associated uncertainty.

2. INSTRUMENT DESCRIPTION

BATSE has been described in detail elsewhere.[1] It consists of eight uncollimated detector modules placed at the corners of the GRO to provide the maximum unobstructed view of the celestial sphere. Each module includes two NaI($T\ell$) scintillation detectors: a relatively thin large-area detector (LAD) optimized for sensitivity and directional response, and a relatively thick smaller-area spectroscopy detector (SD) optimized for energy resolution and wider

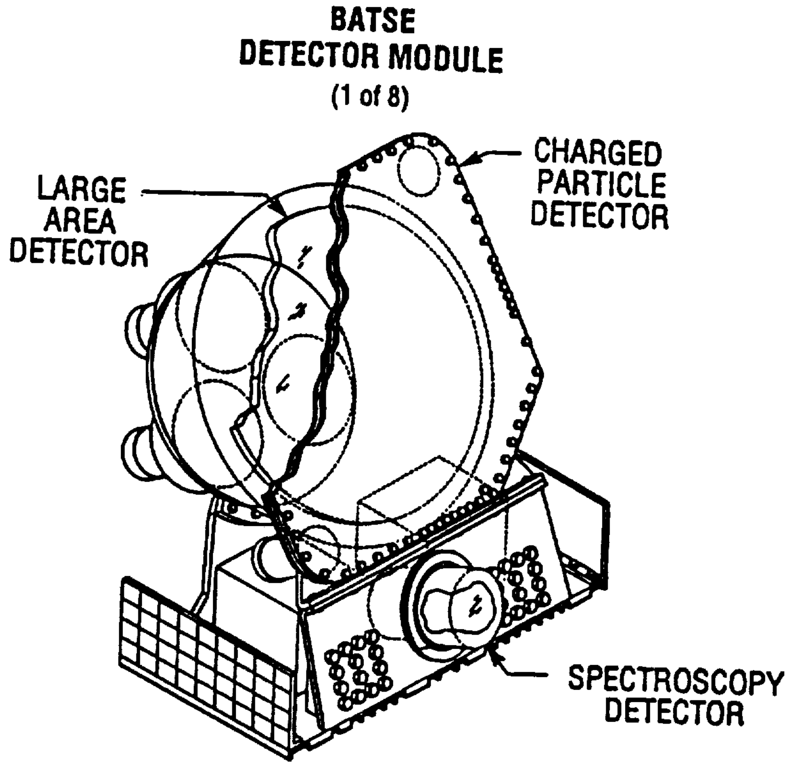

Figure 1: Pictorial representation of a BATSE module.

energy coverage. The anisotropic directional response of the LADs allows location of γ-ray bursts to be determined using BATSE data alone.

The eight planes of the LADs are parallel to the eight faces of a regular octahedron, thus providing nearly uniform sky coverage. The three primary axes of the octahedron are parallel to the three principal axes of the spacecraft. Since the faces of a regular octahedron comprise four intersecting sets of mutually parallel planes, every burst will be viewed by four detectors.

A BATSE module is shown schematically in Figure 1. The LAD contains a NaI(Tℓ) crystal 50.8 cm in diameter and 1.27 cm thick. At low energies where the crystal is opaque to incident radiation, the large diameter-to-thickness ratio of the scintillation crystal produces a detector angular response similar to that of a cosine function. At energies above about 300 keV, the angular response becomes flatter than a cosine. The LADs are uncollimated in the forward hemisphere and passively shielded as described below in the rear hemisphere.

Scintillation light from the detector crystal is viewed by three 12.7 cm photomultiplier tubes (PMTs). The signals from the three tubes are summed at the detector. The light collection technique is different from that usually used with crystal scintillation detectors. Instead of directly coupling the PMTs to the crystal window, a large light-integrating housing is used (Figure 1). The housing is lined with passive lead/tin shielding and is coated internally with a barium sulphate-based white reflector. The passive shielding is effective up to energies of about 200 keV. The front of the LAD is covered by a charged-particle detector (CPD) which uses a plastic scintillator to reject charge-particle-induced events in the LAD.

The SD is an uncollimated NaI(Tℓ) scintillation detector 12.7 cm in diameter by 7.62 cm thick. A single 12.7 cm diameter PMT is directly coupled to the scintillation detector window. The housing of the PMT has a passive lead/tin shield similar to that of the LADs. In order to provide high efficiency at energies as low as 15 keV, the front of the crystal housing is fitted with a 7.62 cm diameter beryllium window. The axis of symmetry of an SD is offset by ~15° from the LAD axis for mechanical reasons. Since the angular response of the SD is more nearly isotropic, there is no scientific requirement for coalignment with the LAD.

Each of the eight BATSE detector modules sends data to the Central Electronics Unit (CEU) which contains hardware and software that accumulates the data into several large RAM memory areas and constructs the BATSE telemetry packet. Telemetry rate limitations require the use of a variety of data encoding and compression strategies. Extensive use of commandable parameters, plus the capability to re-program the flight software after launch, insures that BATSE will have the flexibility to respond to unforeseen conditions in orbit and/or newly discovered γ-ray phenomena.

3. DEVELOPMENT OF DETECTOR RESPONSE MATRICES

A detailed knowlege of the detector response is necessary for spectral analysis and for burst location. The response is formulated in terms of a set of matrices that characterize the detector output for a given energy input. The spectral response functions for the BATSE detectors, particularly the LADs, exhibit significant Compton tails for higher input photon energies. This effect complicates not only the photon spectral deconvolution but also the use of the LADs for reliable burst location. Furthermore, the LADs exhibit variations in light collection across the face of the crystal of ~15%, producing measurable effects on energy resolution and angular response. Several series of calibrations have been performed in order to characterize these effects with sufficient precision to meet the BATSE scientific objectives. Although only portions of the data have been analyzed in detail, it is clear that a sufficient combination of experimental data and simulations exists to assure that the desired instrument performance will be achieved.

In the remainder of this section we discuss the most important calibrations, with emphasis on the systematics of burst location using the LADs. We also briefly describe the Monte Carlo modeling and present some preliminary results of attempts to simulate the laboratory calibrations. A more general discussion of the Monte Carlo methodology and the development of the BATSE response matrices may be found elsewhere.[2]

3.1. Radial response measurements

The light-integrating housing used in the BATSE LADs allows relatively uniform light collection with fewer PMTs than would be required for the more usual design in which PMTs are directly coupled to the crystal window. A radial dependence of the light collection efficiency is, however, observable and has significant consequences for detector performance. The effect is clearly evident in the shape of the full-energy peak measured during laboratory calibrations. Figure 2 is an example of the spectrum in the region of the 662 keV peak of ^{137}Cs when the full area of the detector is exposed to the source. No simple gaussian gives a good fit to the peak shape. A gaussian which provides a good fit to the high-energy side of the peak is clearly a bad fit on the low-energy side. Light collection variations would naturally produce such a response since the interactions in regions from which light collection is poor would result in a lower apparent energy.

In order to characterize the radial response, a series of measurements were performed using a collimated source to illuminate only local regions of the detector front face. As expected, the data showed that the peak response to a collimated source is fitted well by a gaussian and that the centroid of the gaussian shifts to lower pulse height as the radial position increases. The typical centroid shift near the edge is 15%.

Non-uniform light collection can in principle have both azimuthal and radial components. However, it was expected from preliminary measurements with non-flight crystals that azimuthal asymmetry would be relatively unimportant. We therefore attempted to model the peak shape by assuming azimuthal symmetry. In this case, the peak shape p as a function of energy E is given by

$$p(E) = \int_0^R 2\pi r \exp(-\alpha(E - E_0(r))^2)\, dr. \tag{1}$$

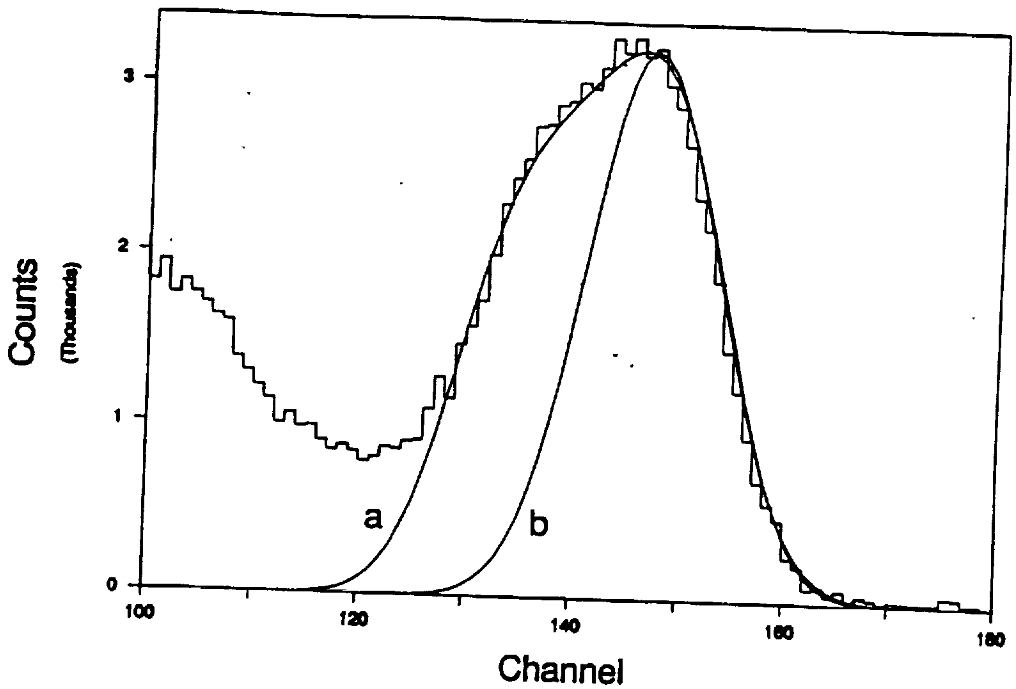

Figure 2: The on-axis response of a typical BATSE LAD to a ^{137}Cs calibration source. Only the region near the full-energy peak is shown. The histogram represents the data. Curve a is a fit to the peak region as described in Section 3.1. Curve b is a Gaussian fit to the data at energies above the peak maximum.

Here $E_0(r)$ is the radial response (*i.e.*, the apparent centroid energy at a distance r from the center), R is the radius of the crystal, and α is an adjustable parameter. Although the analysis is not yet complete, a simple quadratic form for $E_0(r)$ was found to give an acceptable fit to the data examined thus far. Substituting this form into Equation (1) yields a model peak shape which is then fitted to the full-energy peak data by adjusting the parameter α. The resulting shape is shown superimposed on the data in Figure 2, from which it is clear that this model is quite successful at accounting for the non-gaussian shape of the ^{137}Cs peak. Similarly good results have been obtained with line shapes from other calibration sources.

3.2. Angular response measurements

The ability of BATSE to locate γ-ray bursts results from the anisotropic angular response of the LADs. The relative efficiencies and angular response have been measured at a discrete set of energies and angles. The measurements were carried out in a high bay area in an attempt to reduce effects due to the walls and other surrounding materials. A detector module was mounted on a rotatable table such that the LAD principal axis was horizontal and perpendicular to the axis of rotation of the table. The module and table were mounted on a scaffold such that the detector was ~5 m above the floor and ~6 m from the nearest wall. A lead source holder/collimator was mounted at the same height on a separate scaffold located ~12 m from the detector. Spectra were taken for each of seven sources (^{133}Ba, ^{60}Co, ^{57}Co, ^{137}Cs, ^{109}Cd, ^{75}Se, and ^{241}Am) at each of 40 different angles with respect to the LAD principal axis. Monte Carlo simulations are used to determine the response at other values of energy and/or angle.

Figure 3 is an example of the results of the angular response measurements. Shown are ^{137}Cs spectra at various angles from the principal axis of one of the LADs. The decrease in intensity as the off-axis angle increases is evident. Also noteworthy is the shift of the peak toward lower apparent energy for the nearly edge-on (96°) case. Figure 4 shows this effect more clearly. Here the measured shift is shown for two different energies as a function of the

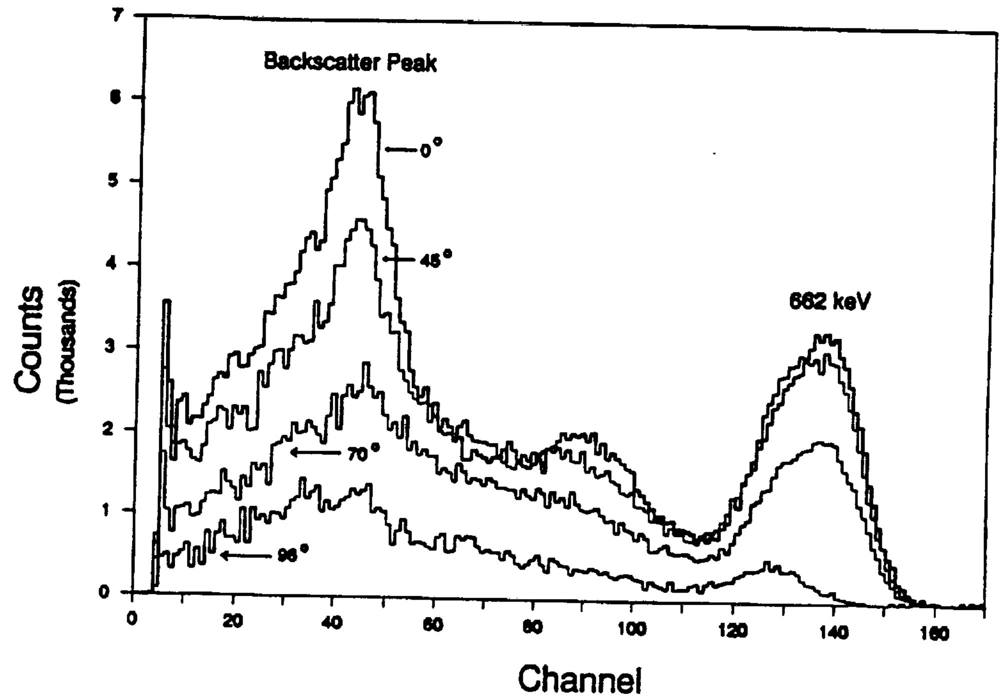

Figure 3: Measured ^{137}Cs spectra obtained at various angles of incidence relative to the LAD principal axis.

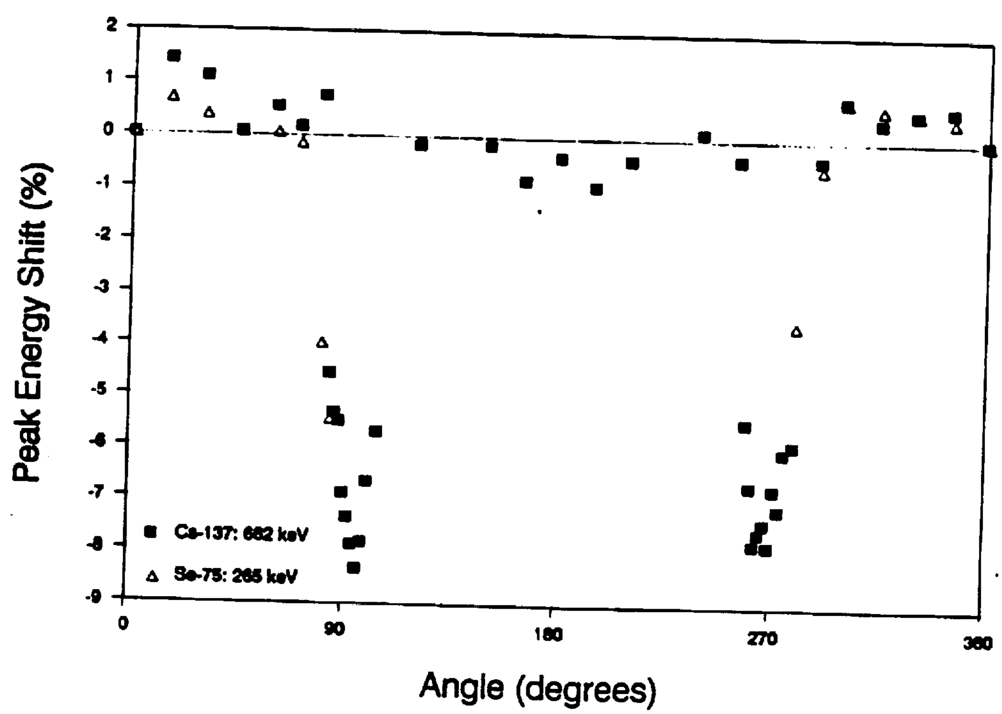

Figure 4: Measured centroid shift *vs.* angle of incidence for two energies. The shaded squares show data for 662 keV (^{137}Cs source) and the triangles (Δ) show data for 265 keV (^{75}Se source).

incident angle. The apparent peak energy is significantly smaller for angles of incidence between ~70° and ~110°, a result which is due primarily to the radial response characteristics. At large off-axis angles the incident γ-rays interact predominantly near the edge of the crystal where the light collection is reduced relative to the center.

3.3. Monte Carlo simulations

In order to reproduce the experimental measurements with Monte Carlo calculations the detector geometry and the test environment geometry must be simulated in sufficient detail. The BATSE methodology is discussed extensively by Pendleton *et al.*[2] The EGS electron-photon shower code[3] is used together with a general geometry routine written by G. N. Pendleton. Detector spectra are produced by convolving the Monte Carlo energy deposition with the measured radial response and statistical broadening. Figure 5 is an example of the simulations of the data from angular response tests. Monte Carlo spectra of ^{137}Cs are shown for incident angles of 0° and 90°. The features seen in the data (Figure 3) are generally well reproduced. The notable exception is the backscatter peak near 200 keV, for which the Monte Carlo simulation produces more events on the low-energy side of the peak than are observed. These events are due to photons that scatter in the test environment before interacting in the detector. However, the spectra shown in Figure 5 were not generated with a complete representation of the angular response calibration geometry; in particular, the large lead collimator was not simulated. Other preliminary simulations which included the lead collimator have been successful in accounting for the detailed shape of the backscatter peak, and it is expected that calculations using a complete geometry will successfully simulate the entire spectrum.

3.4. Absolute efficiency calibrations

In order to measure the absolute efficiency of the detectors, nine modules (eight flight and one proto-flight) were exposed to eight different laboratory standard sources with known actvities (^{241}Am, ^{133}Ba, ^{109}Cd, ^{57}Co, ^{60}Co, ^{137}Cs, ^{203}Hg, ^{22}Na, and ^{88}Y). The sources were located far enough ($\gtrsim$ 280 cm) from the detectors to assure uniform illumination; the source–detector distances were measured to within ±0.05%. In contrast to the angular response calibrations, the absolute efficiency measurements were carried out in a relatively small room, so that nearby materials in the calibration environment have a larger effect on the results. The goals of the calibration were as follows:

1. Measurement of the absolute efficiencies of the LADs and SDs.
2. Measurement of the low-energy attenuation due to the presence of the thermal blankets that surround each module.
3. Verification of the Monte Carlo simulations of the detector response.

The number of photons striking the front of each LAD is determined accurately from the known source activities and the experimental geometry. The Monte Carlo simulations of the calibrations are verified by comparing both absolute intensities and spectral shapes. The success of the simulations for a representative source (^{203}Hg) is illustrated in Figure 6; here the simulations have been normalized to the data solely on the basis of the source activity.

More than 99% of the events in the ^{203}Hg full-energy peak are due to photons that enter the LAD directly without scattering in any of the surrounding material. In the Monte Carlo simulations, no arrangement of materials in the test environment produces a significant contribution to the full-energy peak from photons scattering in the test environment before interacting in the detector. Therefore, comparison of the counts in the measured and simulated full-energy peaks yields an accurate assessment of the absolute detection efficiency. It is clear from Figure 6 that the absolute efficiency is adequately understood.

In the absolute efficiency calibrations the sources were not collimated, so that scattering off objects in the test environment has a more significant effect than for the angular response measurements. Since simulation of all

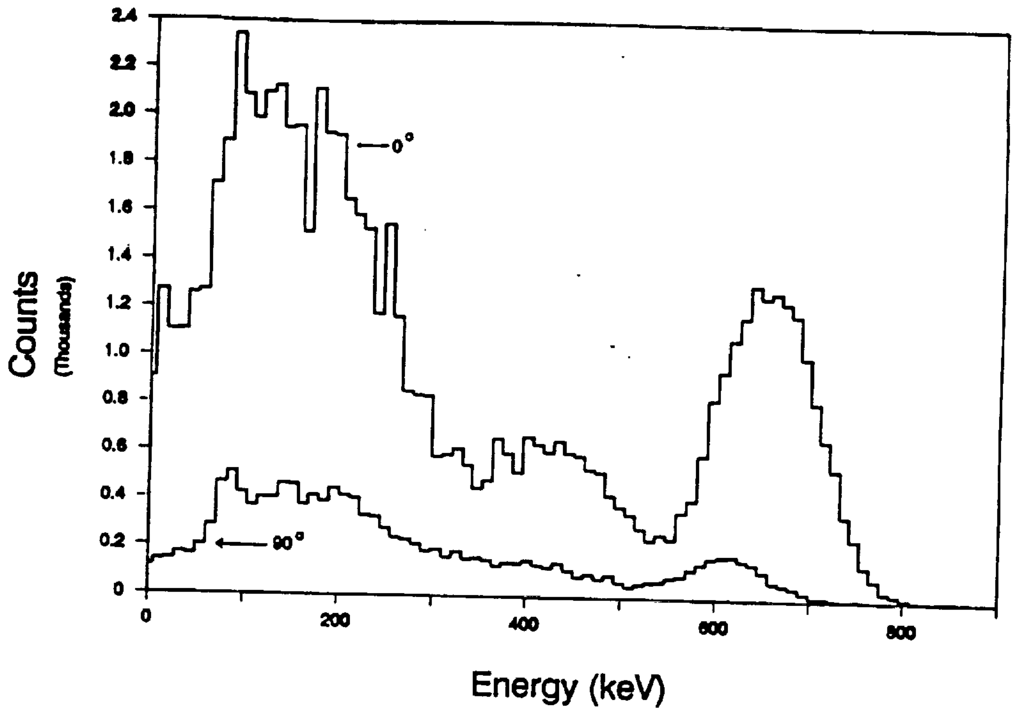

Figure 5: Spectra produced by Monte Carlo simulations of the LAD exposed to a ^{137}Cs source in the Angular Response Test geometry. Spectra for 0° and 90° incidence are shown. The axes have not been normalized to the measured spectra (Figure 3).

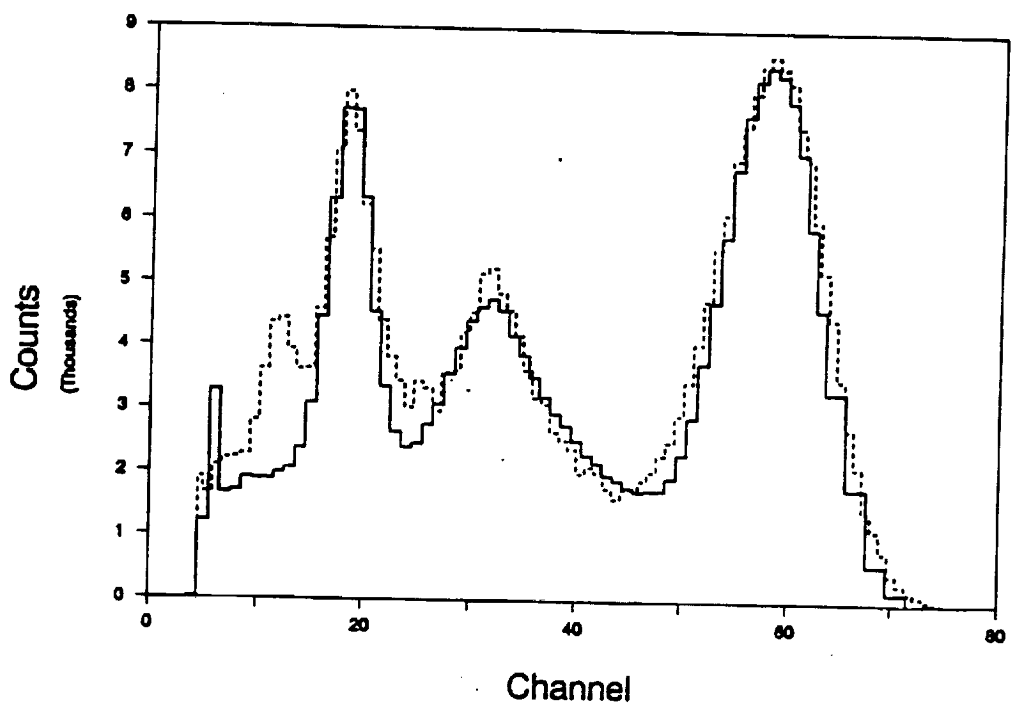

Figure 6: Comparison of measured and simulated spectra of a ^{203}Hg source taken during the LAD absolute efficiency calibrations. The solid histogram represents the data; the dashed histogram represents the simulations.

BATSE Burst Location Uncertainties

Source of Error		$\Delta\theta$
Systematic		
	Detector Efficiences & Calibration	0.4°
	Detector Alignment & Aspect uncertainty	0.2°
	Spacecraft Scattering	0.4°
	Atmospheric Scattering	0.4°
	Subtotal (RMS)	0.7°
Statistical	(Burst size)	
	10^{-7} erg·cm^{-2}	26°
	10^{-6} erg·cm^{-2}	3°
	10^{-5} erg·cm^{-2}	0.4°
	10^{-4} erg·cm^{-2}	0.1°

Table 1: Estimated burst location accuracy

objects is impractical, simplified approximations were used in the simulations, which were designed to show only that the total number of events in the backscatter region could be accounted for.

The effect of the thermal blankets on the spectrum was also determined in the absolute efficiency calibrations. Comparisons of total energy deposited in each detector with and without the thermal blankets verified that the blankets have less than 1% effect on the absolute efficiency over most of the LAD energy range.

4. CAPABILITIES FOR BURST LOCATION

The directions to burst sources will be determined by comparing relative counting rates among the LADs. The concept of using several detectors with anisotropic angular response for determining burst locations was first elaborated by Golenetskii *et al.*[4] For sufficiently strong bursts, the accuracy of the locations thus obtained is limited by various systematic errors. Table 1 summarizes the estimated BATSE burst location uncertainties. Uncertainties in detector response determination are estimated to result typically in a location uncertainty of 0.4°. It is expected that scattering from the GRO spacecraft and the Earth's atmosphere will also be determined well enough to contribute a similar amount to the location uncertainty.

Radiation scattering from the spacecraft normally enters the LAD from behind. Although the light collection cones include some passive lead/tin shielding which reduces this component at low energies, this component is expected to be a significant source of error in burst locations. In order to characterize the effect, measurements of spacecraft scattering using radioactive sources were performed after instrument integration at TRW. The measurements will be supplemented by Monte Carlo calculations which use a detailed mass model of the GRO spacecraft. This should allow reduction of the systematic error due to spacecraft scattering to 0.4° for the typical burst.

Scattering of burst photons in the Earth's atmosphere is also a significant source of systematic uncertainty. This effect is much larger than spacecraft scattering, but can be simulated more easily in this case because of the well-known geometry and composition of the atmosphere. The uncertainty is strongly dependent on the elevation of the burst above the Earth's limb; a value of 0.4° is expected to be attainable for the typical burst. Extensive Monte Carlo modeling of atmospheric scattering has been performed previously.[5] Further studies are planned.

The total systematic error is expected to be somewhat less than 1° for the typical burst. A number of approaches will be used in orbit to confirm the response determination and to reduce systematic errors further. With eight detectors the location is overdetermined. Since each burst is observed directly by four detectors, while only three are needed to compute a location, an estimate of the systematic error is available for each burst. Detectors facing away from the burst, but facing the atmosphere, will provide measurements of atmospheric scattering. Systematic corrections can be improved by using independently-located bursts such as solar flares, bursts located by the interplanetary network, and possibly even orbiting nuclear reactors.

Statistical errors as a function of burst fluence are also provided in Table 1, which indicates that BATSE should be able to determine locations to better than 1° for bursts larger than about 10^{-5} erg-cm^{-2} (*i.e.*, several dozen bursts per year).

5. SUMMARY

The BATSE detectors have been subjected to intensive testing and calibration in order to assure that systematic errors will not compromise the instrument's scientific objectives. In combination with detailed Monte Carlo simulations, the calibrations can and will be used to develop the detector response matrices necessary for reliable γ-ray burst location.

6. ACKNOWLEDGEMENTS

The pre-integration testing and calibration of the BATSE detectors was performed at the Marshall Space Flight Center. We thank the following for their contributions to this endeavor: M. Flora, P. Moore, D. Rice, S. Harris, and M. Brock. We are especially grateful for the resolute efforts of the BATSE Project Manager, Mr. B. J. Schrick, and the BATSE Chief Engineer, Mr. J. D. Ellsworth.

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